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Geometrical Error Identification and Compensation for Grinding Machine by Crankshaft Roundness Measuring

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Tangential point tracing grinding method has many advantages in the precise machining for eccentric parts such as crankshaft pin grinding. But its machining accuracy is based on a very precise geometrical model, which means the geometrical error of the machine tool can induce big outline error. By analysing the motion model of the tangential point tracing grinding, the roundness influence functions are established which respectively indicates the roundness errors caused by grinding-wheel centre height error, grinding-wheel radius error and grinding-wheel feeding error. Then the influence of them on crankpin roundness error are simulated. Now that the geometrical errors of the machining tool are quite difficult to measure, an innovative geometrical error identification and correction methodology is put forward, which identifies the geometrical errors by measuring the roundness of a grinding sample, then corrects the geometrical errors by NC compensating. Moreover, the correction methodology is practically applied in the crankshaft pin grinding in laboratory. The validity and feasibility of the presented geometrical correction methodology is proved by theoretical calculations and off-line roundness measurements. It is indicated that the proposed geometrical error identification and correction methodology emerges good prospect in precise grinding machines.

1. Introduction

Precision has been one of the primary goals of today's manufacturing technology. As a main part of the engine, the crankshaft error can directly affect the mechanical efficiency and the service life of the engine. (XU Dihong et al. 2002) On the other hand, there are many problems lie in the crankshaft grinding like complex shape, low rigidity, multiple error sources, etc. The precise grinding of crankshaft is one of the most serious difficulties of the engine manufacturing. (WU Ganghua et al. 2009; Dongdong Li et al. 2011; Oliveira 2009) To uprate the machining precision, some eccentric-clamping machining methods like tangential point tracing grinding method, following grinding method are applied in the crankshaft manufacturing. These methods reduce the circular error of the crankshaft from the processing mechanic. The tangential point tracing grinding method controls the work-piece rotating axle C and the grinding wheel feeding axle X. So the grinding wheel can tangentially grind the crankshaft pin at any angle. Furthermore, the tangential point tracing grinding is high flexible and need only onetime clamping which makes it many advantages like low cost, high accuracy and production efficiency.(F. Grasso. 2014).On the other hand, the tangential point tracing grinding is based on a precise geometrical model. The geometrical errors of the machine can affect the grinding result directly. The geometric errors of a five-axis machine tool affect the accuracy (Abbaszadeh. 2002). And some geometrical errors like grinding wheel radius variation cannot be measured online. While the height difference between grinding wheel centre and machining tool gyration centre cannot be removed totally. So, the circular errors caused by these factors should be compensated in the NC system (B. Denkena. 2014). The statistic errors in the ordinary cylindrical grinding can only affect the diameter of the shaft parts. But the errors in tangential point tracing grinding can also cause circular errors of the shaft. So if the geometrical errors of the machine can be compensated appropriately, the crankshaft accuracy can be promoted greatly (Ibaraki S et al. 2012).

2. The motion model of crankshaft tangential point tracing grinding

During the grinding, when the crankshaft is rotating, the crankpin rotates as an eccentric circular track around the main journal. By controlling the horizontal position of grinding wheel, the tangential point between wheel

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and crankpin can rotate accordingly. (YU Hongxiang et al. 2011) Finally the tangential point track forms the crankpin outline. The scheme of tangential point tracing grinding method is shown in Figure1.

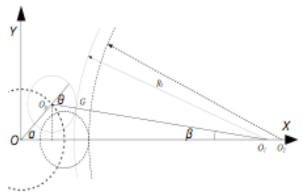

Figure 1: The schematic diagram of tangential point tracing grinding

Taking centre point of the main journal as the origin of the system coordinates, the coordinate XOY is established. So the motion formulas of the grinding carriage (axle X) and the work-piece (axis C) could be expressed as:

$$\begin{cases} x_g = R\cos\alpha + R_p\cos\beta \\ y_g = R\sin\alpha - R_p\sin\beta \\ R\sin\alpha = (R_t + R_p)\sin\beta \end{cases} \tag{1}$$

Where, (X_g,Y_g) is the coordinate of the tangential point, R is the eccentricity of the crankpin, R_t is the radius of the grinding wheel, R_p is the radius of the crankpin, α is the angle between OO_p and OO_1, and β is the angle between O_1O_p and OO_1. O_1 is the centre of the grinding wheel and Op is the centre of the crankpin. So the instantaneous position of wheel centre can be expressed as:

$$d_t = OO_1 = R\cos\alpha + (R_t + R_P)\cos\beta \tag{2}$$

If the tangential point O_p rotates with the angular velocity ω_p, with the parameters of crankpin eccentricity, crankpin radius and grinding wheel radius, the motion function of grinding wheel (axle X) can be concluded as:

$$\begin{cases} \theta = \alpha + \beta = \omega_p t \\ \beta = \arcsin\left(\dfrac{R\sin\alpha}{R_t + R_p}\right) \end{cases} \tag{3}$$

Where, *α* is the crank rotation angle around *O*, *β* is the work-piece rotation angle around O_1, and *θ* is the deflection angle of the tangential point.

3. The simulation and analysis on grinding accuracy effected by geometrical error

The geometrical errors of machine tool that affects grinding accuracy most are grinding wheel height error, grinding wheel diameter error and grinding wheel feeding error. To study how these geometrical errors affect the crankpin roundness, computer simulations are taken accordingly.

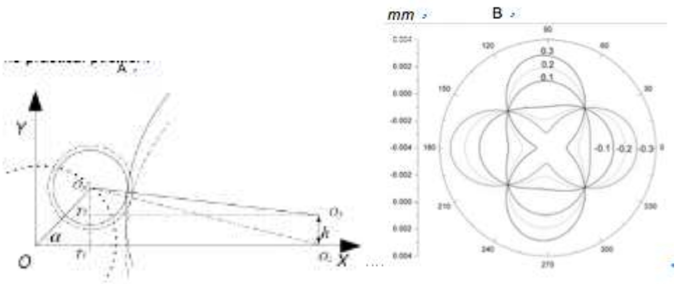

Figure 2: The grinding diagram with grinding wheel height error A) The grinding diagram with higher wheel height B) The crankpin roundness based on different grinding wheel height errors

3.1 The roundness error caused by grinding wheel centre height error

Because of the processing and assembling errors of the components, the grinding wheel centre height and the crank rotating centre height always has difference. When grinding the crankpin, the height error can influence the grinding accuracy. As Figure 2 A) shows, the dashed line shows the theoretical position, the solid line shows the practical position.

For the grinding wheel centre height is higher than the crank rotating centre, let the height difference is *h*. According to the triangle relations from $\Delta O_1O_pT_1$ and $\Delta O_2O_pT_2$, it is easy to get:

$$\begin{aligned} O_1T_1 &= \sqrt{O_pO_1^{\ 2} - O_pT_1^{\ 2}} \\ &= \sqrt{\left(R_t + R_p'\right)^2 - (R\sin\alpha)^2} \end{aligned} \tag{4}$$

So the practical radius of the crankpin is:

$$\begin{aligned} R_p &= O_pO_2 - R_t = \sqrt{O_pT_2^{\ 2} + O_2T_2^{\ 2}} - R_t \\ &= \sqrt{\left(O_pT_1 - h\right)^2 + O_1T_1^{\ 2}} - R_t \\ &= \sqrt{\left(R\sin\alpha - h\right)^2 + (Rt + Rp')^2 - (R\sin\alpha)^2} - R_t \\ &= \sqrt{h^2 - 2Rh\sin\alpha + (Rt + Rp')^2} - R_t \end{aligned} \tag{5}$$

Where, R is the eccentricity of the crankpin, R_t is the radius of the grinding wheel, is the theoretical radius of the crankpin, and α is the rotation angle of the crankpin centre. If the grinding wheel centre is lower than the crank rotating centre, take the h be negative value. The simulation is carried out with the basic parameters shown in the Table 1. And the h are respectively -0.3, -0.2, -0.1, 0.1, 0.2, 0.3 mm.

Table 1: The basic parameters of grinding simulation

Parameter	Value	Parameter	Value
Crankpin radius R_p	25mm	Crankpin eccentricity R	45mm
Wheel radius R_t	300mm	Simulation points per circle n	4096

For the difference between α and θ, it should be calculated before simulation. Base on the different grinding wheel centre height errors, the roundness errors of the crankpin can be acquired. The circular angle is α, namely the crankpin centre rotation angle. And the 6 curves marked with wheel errors are the corresponding crankpin outline diagram. Obviously, the roundness error caused by grinding wheel height has significant phase feature.

3.2 The roundness error affection caused by grinding wheel radius error

During practical grinding, the grinding wheel radius changes because of wearing and thermal deformation. However, the NC system always utilizes the theoretical diameter to calculate the grinding wheel motion. Thus the crankpin roundness error and dimension error accordingly appears.

As Figure 3 A) shows, the dashed line shows the theoretical position, while the solid line shows the practical position. Where the practical grinding wheel is larger than the theoretical one, the crankpin radius can calculated by cosine theorem in the triangle $\Delta O_1O_2O_{p.V}$

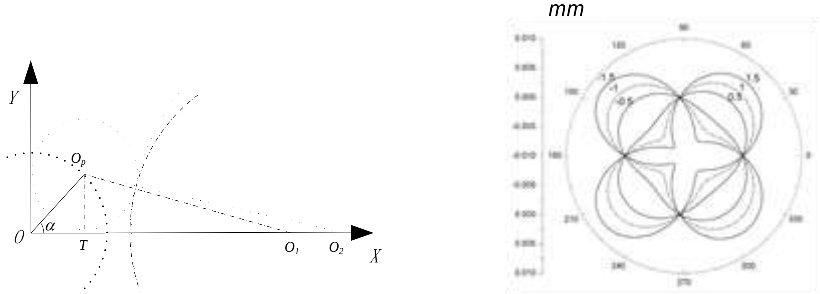

Figure 3: A) The grinding diagram with larger wheel radius than theoretical radius B) The crankpin roundness based on different grinding wheel radius errors

$$
\begin{aligned}
R_p &= O_pO_2 - R_t \\
&= \sqrt{O_1O_2^{\,2} + O_pO_1^{\,2} - 2O_1O_2 \cdot O_pO_1 \cos\angle O_2O_1O_p} - R_t \\
&= \sqrt{dx^2 + (R_p' + R_t')^2 + 2dx \cdot O_1O_p \cdot O_1T / O_1O_p} - R_t \\
&= \sqrt{dx^2 + (R_p' + R_t')^2 + 2dx\sqrt{(R_p' + R_t')^2 - (R\sin\alpha)^2}} - R_t
\end{aligned}
\tag{6}
$$

Where, R_p' is the theoretical radius of the crankpin (namely the target value), R_t' is the theoretical radius of the grinding wheel, and *dx* is the radius error. If the radius is less than theoretical one, *dx* takes a negative value. The simulation is also carried out with the basic parameters shown in the Table 1. And the *dx* are respectively -1.5, -1, -0.5, 0.5, 1.0, 1.5 mm. Base on the different grinding wheel radius errors, the roundness errors of the crankpin can be acquired shown as Figure 3 B). The 6 curves marked with radius errors are the corresponding crankpin outline diagram. Like the affection of the grinding wheel height error, the crankpin roundness error caused by grinding wheel radius also has significant phase feature.

3.3 The crankpin roundness error caused by grinding wheel feeding error

The modern NC (Numerical Control) system and high precise feeding equipment can limit the feeding error within 0.1 µm, especially when the grinding tool is equipped with hydrostatic guide-way driven by linear motor. So the error caused by wheel feeding can be ignored comparing with other two factors.

4. The crankpin roundness error caused by combined errors of wheel height and radius

During the grinding, the main sensitive factors of roundness are grinding wheel height error and radius error. Figure 4 A) shows the combined effect caused by two errors. The dashed line shows the theoretical position, while the solid line shows the practical position with a combined errors of radius errors x_0 and height error h_0.

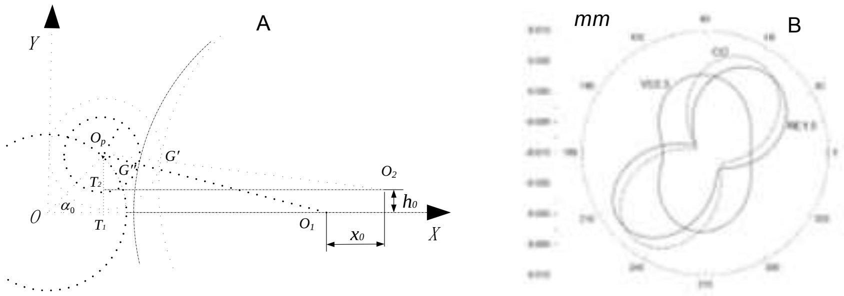

Figure 4: A) The combined effect of bigger grinding wheel radius and higher height B) The combined effect simulation of bigger grinding wheel radius and higher height

According to the triangle $RT\Delta O_PT_1O_1$ and $RT\Delta O_PT_2O_2$, the practical radius of the crankpin can be calculated as:

$$
\begin{aligned}
R_p &= O_pO_2 - R_t = \sqrt{(O_pT_2)^2 + (T_2O_2)^2} - Rt \\
&= \sqrt{(OO_p \cdot \sin\alpha - h_0)^2 + (T_1O_1 + x_0)^2} - Rt \\
&= \sqrt{(R\sin\alpha - h_0)^2 + \left(\sqrt{(R'_p + R'_t)^2 - (R\sin\alpha)^2} + x_0\right)^2} - Rt
\end{aligned}
\tag{7}
$$

The simulation is also carried out with the basic parameters shown in the Table 1. The grinding wheel radius error x_0 is taken as 1.5*mm* and the centre height error h_0 is taken as 0.3*mm*. The simulation is shown in Figure 4 B). Where the line marked with 'RE1.5' is the crankpin outline with a 1.5mm grinding wheel radius error. The line marked with 'VE0.3' is the crankpin outline with a 0.3mm grinding wheel height error. And the line marked with 'CO' is the outline with the combined error with 1.5mm radius error and 0.3 height error.

5. The error analysis of crankpin roundness caused by grinding tool geometrical error

The radius error and centre height error of the grinding wheel are two main affecting geometrical errors on crankpin grinding. By taking a series of combination of the two kinds of errors, a series of simulation are carried out. The simulating results show that the roundness errors caused by one kind error have certain phase characteristic (Bringmann B, Knapp W, 2009). Then the frequency domain analysis of the discrete crankpin points are taken by utilizing the FFT method. The analysis shows that the roundness error of the crankpin has distinct frequency domain characteristic. (Manouchehr et al. 2013) According to the differential element method and theoretical analysis, when the small geometrical errors are within a certain range, the amplitude in frequency domain and geometrical errors have good linear relationship. Therefore, based on the basic parameters like crankpin target radius and eccentricity of the crankpin , taking a series of radius errors(*Re*) and centre height errors(*Ve*) of the grinding wheel, a series of crankpin roundness errors can be calculated. And a certain roundness error corresponds to a certain geometrical error. In other words, if the geometrical errors are subdivided into very small ladders, the roundness errors can be related with the geometrical errors very subtly.

Projecting the roundness error caused by combined errors to the sensitive direction can obtain the error caused by the corresponding single error. (Yi Z et al. 2013)To acquire the radius error and height error of the grinding wheel, the theoretical roundness errors caused by them should be calculated first. Then a sample crankpin should be grinded on the tool. After grinding, the outline of the sample should be measured and project the error value to the sensitive direction respectively. Finally the corresponding error of the grinding wheel height and radius can be obtained by comparing them to the theoretical errors and linear calculation.

6. Test

As Figure 5 shows, a tangential tracking grinding machine for crankshaft pin is constructed in the lab.

Figure 5: The test system of the crankpin tangential point tracing grinding

The work-piece turning axle namely the C axle is driven by CYTEC CRT/350 rotary table. The Heinz Fiege MSP230 spindle is adopted as the grinding wheel spindle. The servo system is SIEMENS SIMODRIVE 611D system. The signal processing is based on the industrial control computer and the *ZJNU-CG* control system which is developed by the study group. Based on the model of the tangential grinding, the *ZJNU-CG* control system can detect the crankpin groundness and exchange data with the computer with TCP/IP protocol.

During the test, a brand-new grinding wheel is used and its radius is set intentionally with 0.3mm error in the NC system. For the objectively existing grinding wheel height error, it is set intentionally as zero in the NC system. Thus, the radius error and height error of the grinding wheel are accurately applied to the grinding tool.

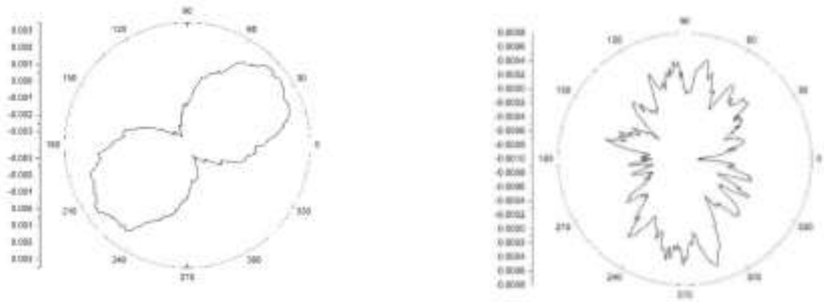

Figure 6: A) The sample roundness without error compensation B) The roundness with compensation

Figure 6 A) shows the sample roundness data without the geometrical error compensation. The sample roundness is measured by Marposs P7 measure system. The peak-peak value of the roundness error is 5.62μm and located at 32º-212º connecting line. Project the value to the sensitive direction 0º-180º connecting line and 45º-225º connecting line respectively. Then the geometrical error can be obtained by comparing to the theoretical value and linear calculating. The grinding wheel radius error is 0.32mm and the centre height error is -0.103mm. Then the geometric errors are lead into the grinding machine NC system to compensate the circular error in the next grinding. When the compensation grinding is finished, the circular error of the sample is measured again and shown in Figure 6 B). The peak-to-peak circular error dropped to 1.2μm. The circular error caused by geometric error has been reduced effectively. The errors left are mainly caused by the non-repetitive deviations like thermal deformation, pairing element friction and nonlinear vibration, etc. Obviously, the grinding accuracy can meet the manufacturing demand after NC compensation

7. Conclusions

To identify and compensate the geometrical error of the tooling machine, an error identification approach is proposed which can get the geometrical errors from the specimen circular errors. Firstly, the motion model of the grinding was built which can describe the grinding procedure well. Then the theoretical outline equation can be concluded from the shaft grinding motion model. Then the outline error at each angle can be acquired by on-position measuring. Secondly, utilizing the proposed approach, the types and values of the geometrical errors can be identified conveniently just by measuring the roundness of the grinding sample. Finally a test machine for crankshaft grinding is constructed. The error identification approach is verified by testing and measuring a series of crankshaft pins. It can identify the geometrical errors of the machine from the sample roundness errors. Then the errors can be compensated in the NC system. It indicates the validity of the proposed approach, which may be potential applicable in the ultra-precision manufacture field.

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